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Three Phase Auto-tuned Shunt Hybrid Filter for Harmonic and Reactive Power Compensation

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Abstract

Hybrid filters are highly recommended for harmonic and reactive compensation in existing installations. Since current harmonic compensation can limit voltage harmonics also to a great extent, shunt hybrid filters are preferred. The traditional shunt hybrid filter consists of shunt passive and shunt active filter. Here, shunt passive filter provides fixed compensation at all load conditions. Therefore, probably at low load conditions, shunt passive filter acts as major consumer. This embarrassing situation can be avoided by replacing traditional shunt passive filter with the shunt auto-tuned passive filter. The shunt auto-tuned passive filter uses an ANN based controller to select passive filter components to provide adequate harmonic and reactive compensation under all load conditions. Remaining harmonic and reactive power compensation are provided by ANN based active filter. The performance of the proposed hybrid filter was tested by simulation and laboratory experiments under various source/load conditions and the results show that the proposed shunt hybrid filter is adaptive to varying source/load conditions.

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Keywords: Neural Networks; Shunt auto-tuned Hybrid filter; digital controller.

1. Introduction

Non-linear loads such as adjustable speed drives, UPS, inverters, and similar power electronic equipment generate distortions in current and voltage in power distribution systems. These devices also cause power quality issues such as reactive power burden, excessive neutral currents, unbalanced currents and low efficiency. To limit the problems created by harmonics, IEEE 519 guidelines are recommended.

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Hence to meet IEEE standards, many harmonic mitigation techniques are developed. Initially, various configurations of passive filters were developed to provide low or high impedance to harmonics such as shunt, or series or their combinations. They are less expensive, but are not desirable in industries due to their shortcomings such as resonance, fixed compensation, bulky size etc. [1-2]. To avoid these problems with passive filters, active filters are developed. Active filters are switch mode power electronic converters to inject harmonic currents in equal and opposite in phase at point of common coupling(PCC) so that utility need to supply only the distortion free currents[3-6]. However, the VA rating of the power electronic converter used as the active filter becomes very large. Hence, the applications of active filters are limited.

Hybrid filters combine both passive and active filters retaining their advantages, i.e. the VA rating of the active converter is reduced as much as possible in order to reduce the overall cost, electromagnetic interference and losses. Different configurations of hybrid filters were developed. In this work, the shunt hybrid filter is a combination of shunt auto-tuned passive filter and shunt active filter. The traditional shunt passive filter elements are designed to compensate for the reactive power under rated load conditions. But as the load on the system varies, reactive power demand varies, whereas traditional filter provides fixed compensation always. Many different types of harmonic filters were reported [7-14]. Hence ANN based auto-tuned shunt hybrid filter was suggested by the authors which can supply variable reactive power compensation. The performance of this shunt hybrid filter was analyzed under various source/load conditions in a test system.

2. Auto-tuned Shunt Hybrid Filter

The auto-tuned passive filter is the filter made tunable by automatically switching the capacitance or by varying the inductance. An ANN based controller [1] senses the source voltages and load currents and accordingly selects suitable capacitors (TSC) and tap positions of inductors (TSR) for the passive filters. The ANN controller predicts switching status of Thyristor switched Capacitors and Tapping positions of Thyristor controlled reactors used for fifth and seventh harmonic compensation. To improve power quality, the auto-tuned filter components are selected such that they can provide maximum reactive power demand of the load (7000 VAR). The 5^{th} and 7^{th} harmonic passive filters can provide 50% (3500 VAR each).The capacitors in TSC units are designed such that the capacitor units provide reactive power requirement by the load at fundamental frequency. The corresponding inductive reactance of TSR unit in 5^{th} harmonic filter is calculated on the concept that TSC-TSR filter provides the minimum impedance path at 5^{th} harmonic frequency (ie. $X_L=X_C$).The capacitor values in 5^{th} harmonic filter are selected as 30μF(500 VAR), 60μF(1000 VAR) and 120μF(2000 VAR) respectively. The various settings possible in TSC-TSR filter and the corresponding reactive power supplied are shown in Table I.

Table 1. Auto-tuned Shunt Hybrid Filter

C_1 30μF	C_2 60μF	C_3 120μF	5^{th} harmonic Inductor TCR(mH)	7^{th} harmonic Inductor TCR(mH)	Tap setting	
ON	OFF	OFF	13.48	6.87	1	500VAR
OFF	ON	OFF	6.73	3.44	2	1000 VAR
ON	ON	OFF	4.49	2.29	3	1500 VAR
OFF	OFF	ON	3.37	1.72	4	2000 VAR
ON	OFF	ON	2.70	1.38	5	2500 VAR
OFF	ON	ON	2.25	1.15	6	3000 VAR
ON	ON	ON	1.92	0.981	7	3500 VAR

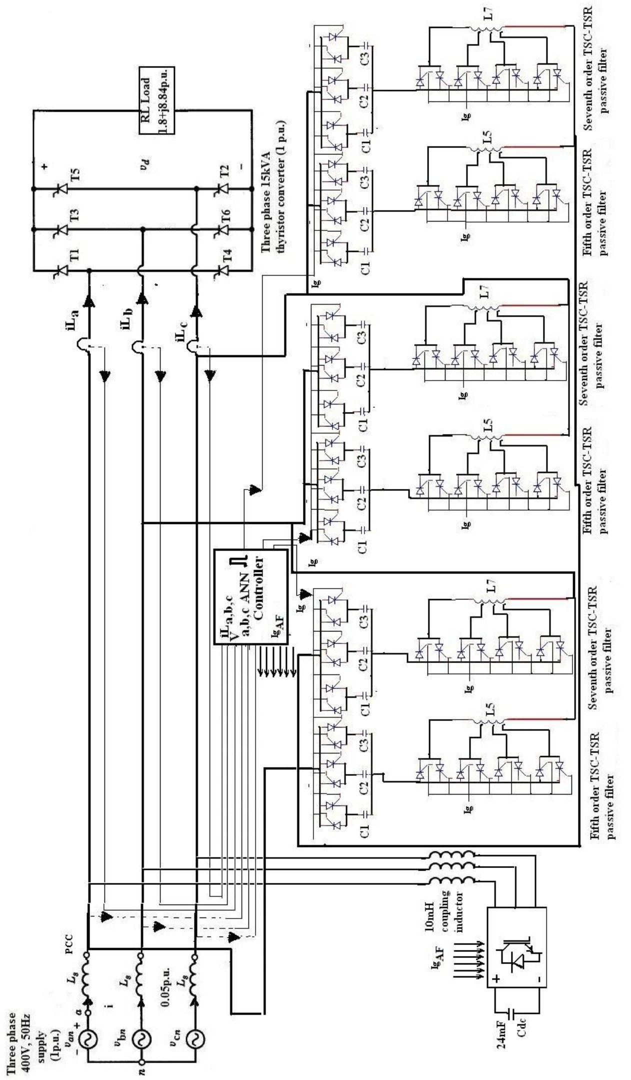

Fig.1. Auto-tuned Shunt Hybrid Filter

Based on the data in above table, 75 training patterns are tabulated with varying reactive power demand from 0 VAR to 7500VAR.The corresponding ON/OFF status of TSCs and tap positions of TSRs are obtained with help of Table 1. The network was trained using 50 training patterns with performance goal of 0.001 and 1500 epochs. The back propagation learning rule is used to train nonlinear multilayered network. The weights and biases of networks are adjusted to minimize sum squared error of the network. Derivatives of error, delta vectors are calculated for networks output layer and back propagated through the network until delta vectors are available for each hidden layer. Output variables are taken as the ON/OFF status of TSCs for 5th harmonic filters (same as for 7th harmonic filters) and tap settings of TSRs for 5th and 7th filters. The ANN controller is simulated as an embedded MATLAB function using SIMULINK toolbox for controlling the TSCs and TSRs . TSC-TSR based passive filters tuned to 5th and 7th harmonic frequencies are connected in parallel as harmonic sinks. The ANN based digital controller receives the load currents and the source voltages at the point of common coupling (PCC) as inputs. Based on the appropriately tuned knowledge base, the ANN selects the proper percentage combination of the passive filter elements.

The active power filter uses Icosϕ algorithm[6] in this work. In the Icosϕ algorithm, the fundamental component of the active part of the load current is deduced from the load current in each phase using a second order low pass filter tuned to fundamental frequency and sample and hold circuits. This gives the amplitude of the desired mains current in each phase. The three-phase mains voltages are used as templates to generate unit amplitude sine waves in phase with the mains voltages. The desired mains currents are then computed as the product of the amplitude ' Icosϕ' and the unit sine wave for each phase. In the case of adaptive shunt hybrid filter, the three phase source voltages, fundamental components of line currents (i_{La}, i_{Lb} and i_{Lc} in Figure 1), switch ON/OFF status of adaptive shunt passive filter elements, and reference compensation currents are selected as training data. The inputs of ANN network are the three phase source voltages, fundamental component of line currents. The output of ANN are switching status of TSC and TSR, and three phase reference compensation currents. Three phase reference compensation currents are compared with actual filter currents to generate switching pulses for IGBTs in shunt active filter. With the help of training data, back propagation neural network was trained with MATLAB using 500 training patterns to achieve performance goal of 0.001 and 2500 epochs. Levenberg-Marquardt algorithm is used for training. The weights and biases of networks are adjusted to minimize sum squared error of the network. The ANN was developed using MATLAB. The ANN comprises of three layers: the input layer (6 neurons), output layer (7 neurons), first hidden layer (6 neurons) and second hidden layer (6 neurons).

3. Simulation Results

The three-phase system simulated in MATLAB/SIMULINK consists of three-phase voltage applied to a 15kW rated inductive load through a diode bridge rectifier. A stiff source is considered and source impedance has been kept at a practical value of 5%.

3.1. Without filter

The performance of diode bridge rectifier with inductive load was studied under balanced/unbalanced/distorted source and balanced/unbalanced load conditions.

(i) Balanced source and balanced load: The system was simulated under balanced source and balanced load conditions. A three-phase 400V voltage applied to the inductive load through a diode bridge rectifier.

(ii) Unbalanced source and balanced load: The system was simulated under unbalanced source and balanced load conditions. A three-phase unbalanced voltage (Phase A: 325V∠0°, Phase B: 425V∠-135°, Phase C: 227V∠135°) applied to the inductive load through a diode bridge rectifier.

(iii) Balanced source and unbalanced load: The system was simulated under balanced source and unbalanced load conditions. Unbalanced Load is introduced in the three phases by adding additional star connected load in R (15%), Y (5%), and B (24%) phases respectively in parallel with nonlinear load.

(iv) Distorted source and balanced load: The system was simulated under distorted source and balanced load conditions. Distortion is introduced in source voltage by having third harmonic (100 V, about 30% of fundamental) and fifth harmonic (100V, about 30% of fundamental).

$$\begin{aligned}
&\text{Distorted voltage (phaseR)} = v1\sin\omega t + v3\sin3(\omega t) + v5\sin5(\omega t)\\
&\text{Distorted voltage (phase)} = v1\sin(\omega t-120°) + v3\sin3(\omega t-120°) + v5\sin5(\omega t-120°)\\
&\text{Distorted voltage (phaseB)} = v1\sin(\omega t+120°) + v3\sin3(\omega t+120°) + v5\sin5(\omega t+120°) \qquad (1)
\end{aligned}$$

Results show that the ac mains current has considerable harmonic contents under different operating conditions, if filter is not provided. Hence, active filter is designed to check its performance in harmonic and reactive power compensation.

3.2. With Active filter

The circuit for Icosϕ algorithm was simulated in MATLAB/SIMULINK and used to control shunt active filter. The system was simulated under balanced/unbalanced/distorted source and balanced/unbalanced load conditions.

(i) Balanced source balanced load:

The addition of active filter shows that the harmonics in source current is highly reduced and THD is within limits. The source voltage and current are in phase and sinusoidal. Hence perfect reactive compensation is done. However, it takes time delay more than 1 cycle for perfect compensation.

(ii) Unbalanced source and balanced load: Simulation results in Table 2 show that the fundamental component of source current is almost average of real components in each phase. The harmonics in source current is highly reduced and THD is within limits. Simulation results show that, with active filtering, the source voltage and current are made in phase and sinusoidal and perfect reactive compensation is done. However, unbalance in source voltage is not corrected, since shunt active power filters are applied.

(iii) Balanced source and unbalanced load: Simulation results in Table 2 show that the source current is almost balanced in each phase. The harmonics in source current are within limits. Simulation results show that, active filter can provide perfect reactive compensation also.

(iv) Distorted source balanced load: Table 2 shows that the harmonics in source current is highly reduced. Simulation results show that, with active filtering, the source voltage and current are made in phase and perfect reactive compensation is done. However, distortion in source voltage is not corrected, since shunt active power filters are applied.

Table 2 shows harmonic spectra in source current loaded after the installation of shunt active filter with Diode bridge rectifier feeding inductive load under various system conditions. It can be seen from Table 2 that the shunt active filter effectively reduces the harmonic content of the source current and provides accurate reactive power compensation also, but it takes a compensation time of more than one cycle. In the next stage, auto-tuned shunt hybrid filter was attempted as an economic option.

3.3. With Auto-Tuned Shunt Hybrid Filter

It is a combination of shunt auto-tuned passive filter and shunt active filter. In the passive filter designed, seven tappings are set on TCR unit. The tappings are provided in 5th filter with inductances 1.92mH, 2.25mH, 2.70mH, 3.37 mH, 4.49 mH, 6.73 mH, and 13.48 mH respectively. Similarly, seven tapings are set on TCR unit in 7th filter with inductances 0.981mH, 1.15mH, 1.38mH, 1.72mH, 2.29mH, 3.44mH, and 6.87 mH respectively.

At each load condition, the ON/OFF status of TSCs and tap settings of TSRs are determined, such that each TSC of the 5th and 7th order filters provide 50% of required reactive power demand each. The corresponding tappings on TCR are selected such that filter can be tuned to fifth or seventh harmonic frequency. The source voltages and load currents are selected as input variables of the ANN network. Output variables are taken as the ON/OFF status of TSCs for 5th harmonic filters (same as for 7th harmonic filters) and tap settings of TSRs for 5th and 7th filters. The network was trained using training patterns with performance goal of 0.001 and 1500 epochs.

To study its effectiveness to improve the power quality, performance of shunt auto-tuned hybrid filter was studied under various source/load conditions such as balanced source and balanced load, unbalanced source balanced load,

Table 2 . Harmonic spectra in source current loaded after the installation of shunt active filter with Diode bridge rectifier feeding inductive load under various system conditions.

Source/load	Fundamental component of load current (rms)(A)			Fundamental component of source current (rms)(A)			THD in load current (%)			THD in source current (%)		
Balanced source balanced load	17.3	17.3	17.3	17.8	17.8	17.8	18.4	18.4	18.4	1.7	1.7	1.7
Unbalanced source balanced Load	20.2	27.6	20.2	23.6	23.6	23.6	21.2	27.9	45.4	1.1	1.1	1.1
Balanced source unbalanced Load	20.1	21.7	18.0	20.6	20.6	20.6	22.7	21.4	28.9	1.5	1.5	1.5
Distorted source balanced Load	18.2	18.3	18.3	18.3	18.3	18.3	29.3	29.3	29.4	1.46	1.46	1.46

Table 3 - harmonic spectra in source current after the installation of shunt auto-tuned hybrid filter

Source/load	Fundamental component of source current(rms)(A)			THD in source current (%)		
Balanced source balanced load	27.97	27.97	27.97	1.51	1.52	1.49
Unbalanced source balanced Load	34.8	34.8	34.8	2.31	2.35	2.34
Balanced source unbalanced Load	26.32	26.32	26.32	2.94	2.92	2.93
Distorted source balanced Load	27.1	27.1	27.1	2.01	1.98	1.97

balanced source unbalanced load and distorted source balanced load and results are shown in Fig.2(a),Fig.2(b),Fig.2(c) and Fig.2(d) respectively. Table 3 shows harmonic spectra in source current after the installation of shunt auto-tuned hybrid filter with Diode bridge rectifier feeding inductive load under various system conditions. Simulation results show that the auto-tuned shunt hybrid filter can also provide effective compensation. Table 4 shows performance comparison of shunt active filter and shunt auto-tuned Hybrid Filter. According to comparative study in Table 4, it can be seen that the two power quality improvement techniques mentioned in the paper can provide better harmonic compensation. Also, the size of the active filter can be reduced in the case of shunt auto-tuned hybrid filter.

4. Experimental Studies

The experimental studies are carried out in a three phase system and a set of results at source voltage of 230V (rms)/phase under various source/load conditions are explained. The auto-tuned shunt hybrid filter, combination of ANN based shunt active and auto-tuned shunt passive filter, is used in this work. The passive filter is designed for

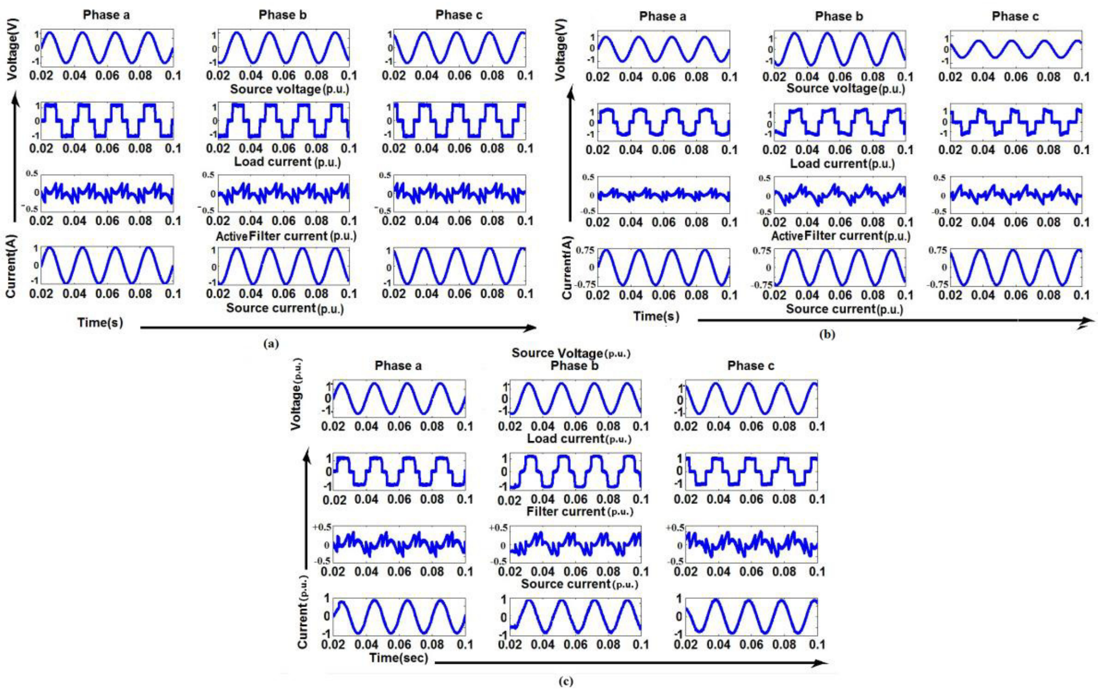

Fig. 2. Performance of test system with shunt auto-tuned hybrid filter under various conditions

Table 4 Performance comparison of shunt active filter and shunt auto-tuned Hybrid Filter

	Without filter	With active filter	With Auto-tuned hybrid filter
Fundamental source current(rms)(A)	17.3	17.8	21.78
THD in source current (%)	18.4	1.7	1.51
Filter current(rms)(A)	-	4.95	1.84
Filter kVA	-	3.5	1.27
% of Active filter size	-	100%	63%
Correction time	-	30ms	20ms

100% VAR compensation and it is tuned to the sixth harmonic so as to avoid resonance condition and to sink both 5^{th} and 7^{th} harmonic currents to certain extent. This will reduce the size of the passive filter and hence the loading on the source also. The steps of inductor-capacitor combinations for auto-tuned passive filter are selected as 2kVAR (5mH-80μF), 3.5kVAR (20mH-20μF) respectively. For the given load, the combination of 2kVAR is selected as the most optimized filter combination and it improved input power factor to unity and THD is highly reduced. The test results are analyzed using FLUKE make power quality analyzer. Fig. 2 shows the performance of test system with the proposed Auto tuned hybrid filter.

5. Conclusion

This paper presents a novel hybrid filter topology and its control which enable practical implementation of hybrid filters with reduced converter rating for high power loads. It is combination of ANN controlled shunt active filter and shunt auto-tuned passive filter. A comparison with active filters show that the proposed approach has the lowest converter rating. The effectiveness of the control method is verified using simulations and is further validated with results from a laboratory prototype. The test results show that proposed hybrid filter can compensate for balanced and unbalanced nonlinear load currents and also adapt itself to compensate for variations in nonlinear load currents. The adaptive shunt hybrid filter is capable of providing effective harmonic and reactive compensation in comparison with the adaptive shunt passive filter and ANN controller based shunt active filter. Source current harmonics are within IEEE standard limits. Both the controllers for adaptive shunt passive filter and ANN controller based shunt active filter can be programmed in the same chip. Hence it can be duplicated in large quantities.

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